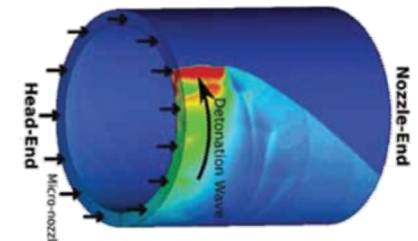
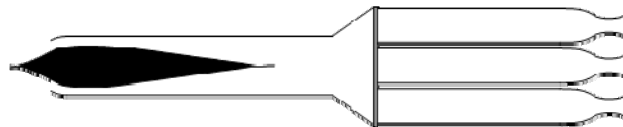
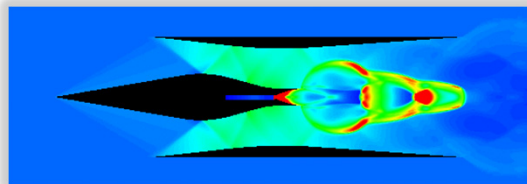
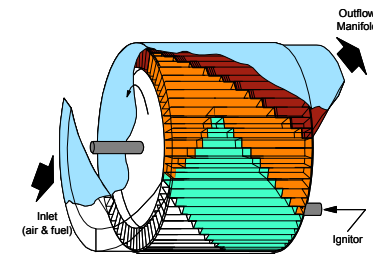
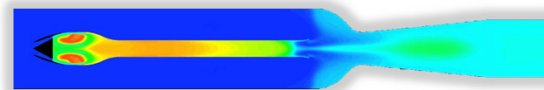
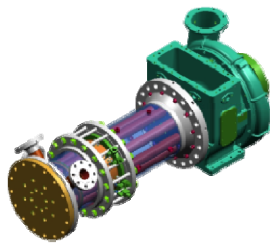




# Pressure Gain Combustion 101

Daniel E. Paxson  
*NASA Glenn Research Center  
Cleveland, Ohio*

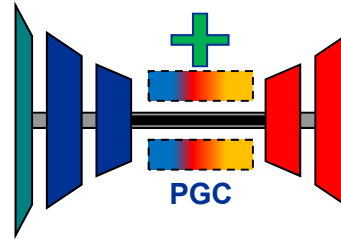


Pressure Gain Combustion Overview:  
Principles, Operation, and Applications  
Propulsion and Energy 2018  
Cincinnati, Ohio  
July 9-11, 2018



## Outline

- What is Pressure Gain Combustion (PGC)?
- Fundamental Thermodynamics
- Benefit Examples
- Implementation Strategies



## What is Pressure Gain Combustion?

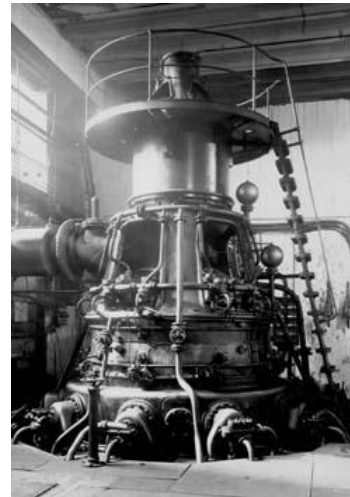
*PGC<sup>†</sup>: A fundamentally unsteady process whereby gas expansion by heat release is constrained, causing a rise in stagnation pressure\* and allowing work extraction by expansion to the initial pressure.*

<sup>†</sup>The term “Pressure-Gain Combustion” is credited here to the late J.A.C. Kentfield

\*Conventional combustion incurs a total pressure loss

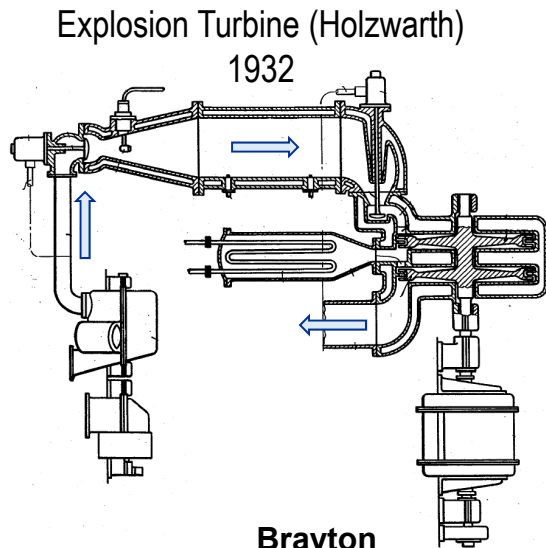
The concept actually is old...

Holzwarth  
Explosion Turbine  
1914



**The Implementation Approaches, Analysis Tools, and Design Capabilities Are New**

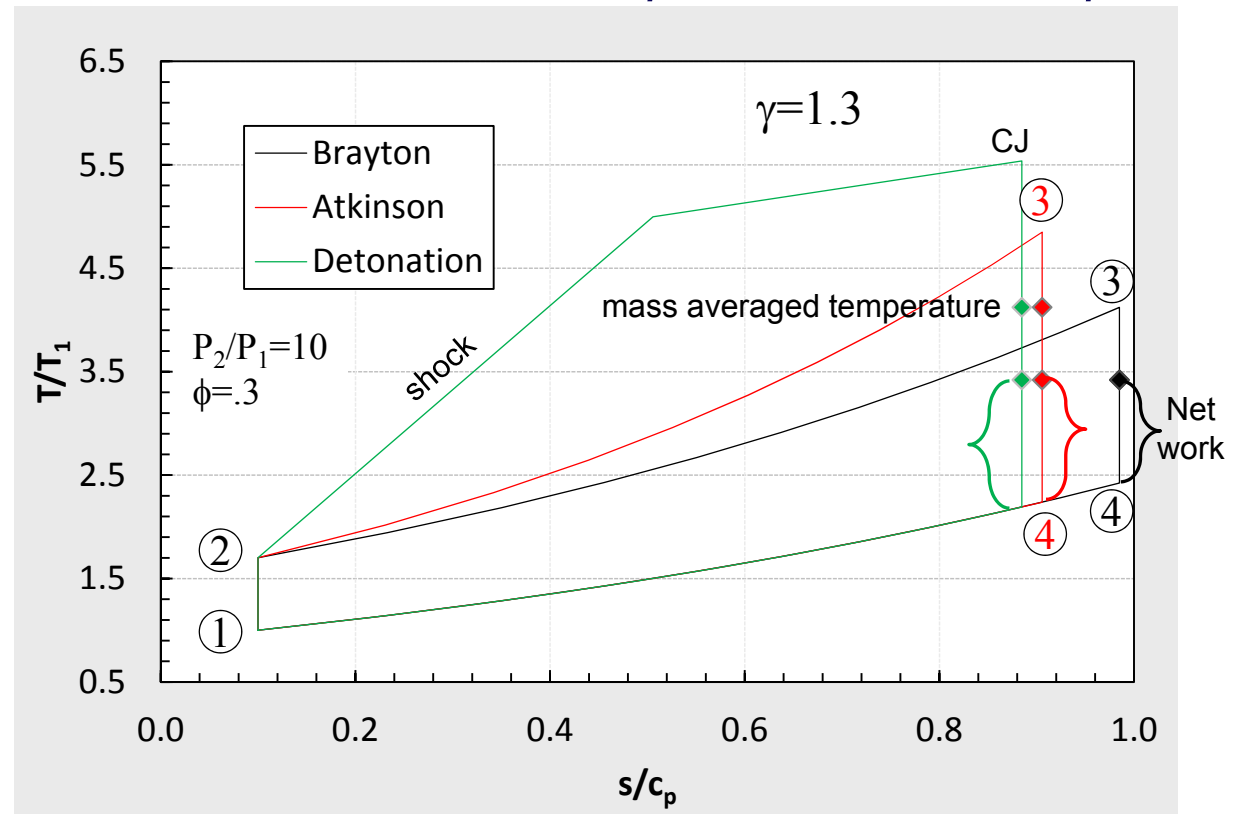
# Fundamental Thermodynamics



**Brayton**  
 1-2: Isentropic (adiabatic) Compression  
 2-3: Isobaric Heat Addition  
 3-4: Isentropic Expansion  
 4-1: Isobaric Heat Rejection

**Atkinson**  
 1-2: Isentropic (adiabatic) Compression  
 2-3: Isochoric Heat Addition  
 3-4: Isentropic Expansion  
 4-1: Isobaric Heat Rejection

## Identical Mechanical Compression, & Heat Input



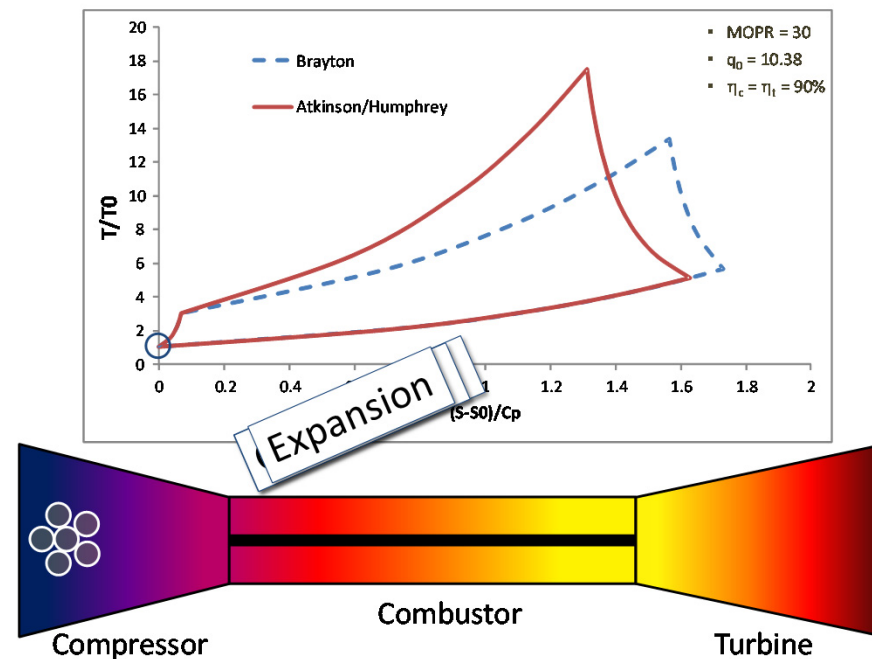
- PGC expands by gasdynamic conversion to kinetic energy (e.g. blowdown)
- Flow to turbine is fundamentally unsteady, and/or spatially non-uniform
- Peak Atkinson Temperature is only momentary



# Fundamental Thermodynamics

## Animation of a Representative PGC Cycle With Turbomachinery

- Illustrates essential concepts
- Demonstrates the most basic acceptable level of modeling
- More quantitatively valuable than might be expected.

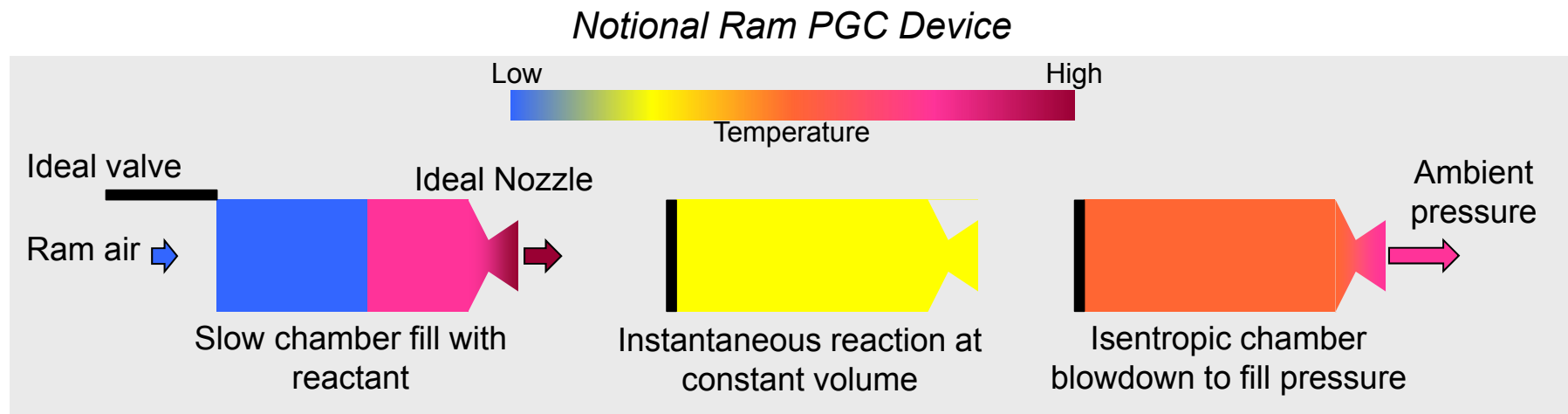




# Fundamental Thermodynamics

## PGC in Notional Ram Device

- High speed inlet compresses
- Mechanical combustor inlet valve envisioned
- Pressure gain converted to kinetic energy via unsteady nozzle



Pressure Rise Provides Increased Availability to Nozzle



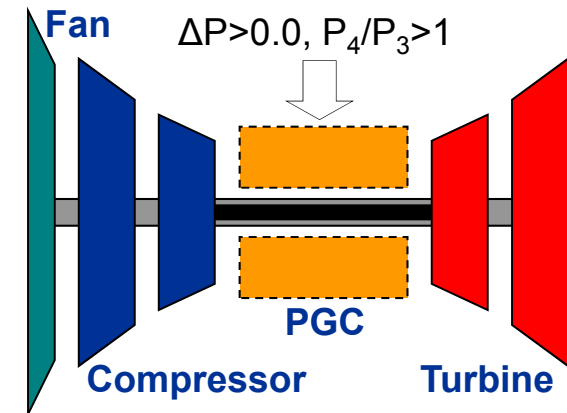
## Example Benefits

### PGC for Gas Turbines

Two specific engines considered

$T_{t4}$ ,  $T_{sp}$  fixed for turbofan (BPR varied)

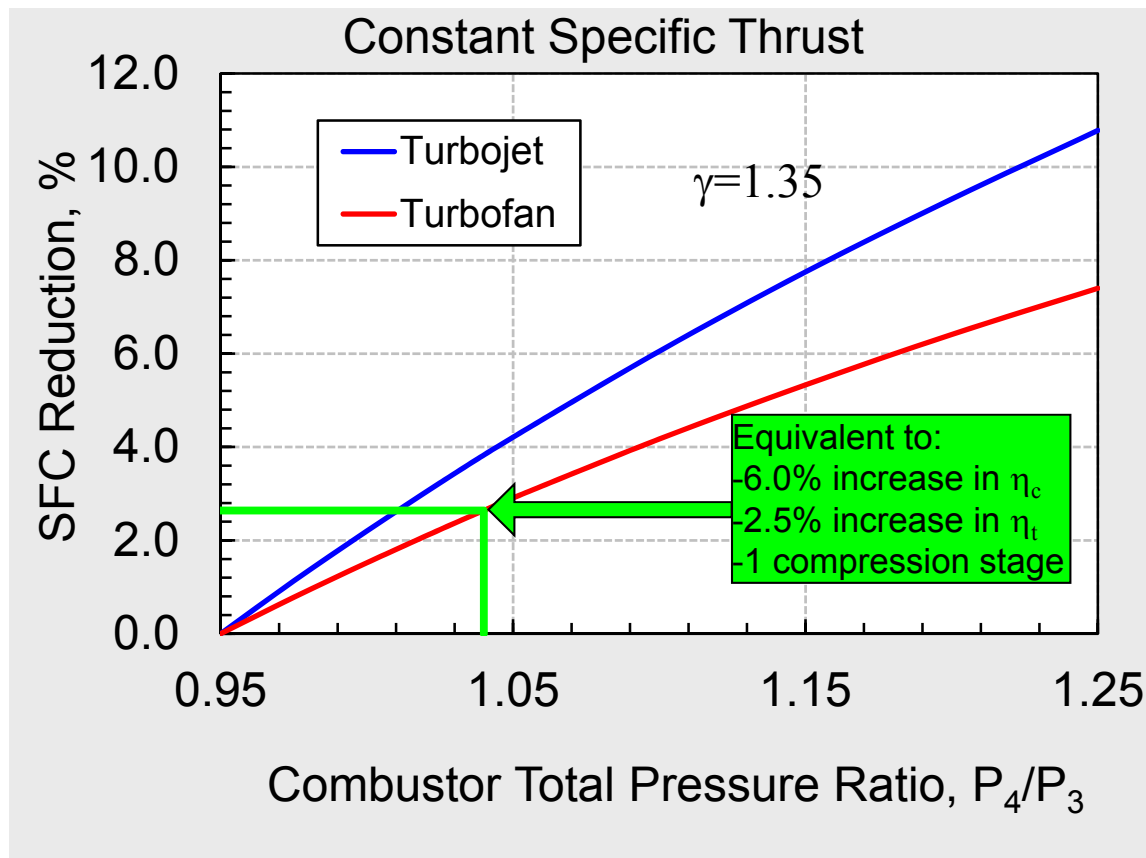
$T_{sp}$  fixed for turbojet ( $T_{t4}$  varied)



Engine Parameter	Turbofan	Turbojet
OPR	30.00	8.00
$\eta_c$	0.90	0.90
$\eta_t$	0.90	0.90
Mach Number	0.80	0.80
$T_{amb}$ (R)	410	410
$T_{t4}$ (R)	2968	2400
Burner Pressure Ratio	0.95	0.95
$T_{sp}$ (lb <sub>f</sub> -s/lb <sub>m</sub> )	18.26	75.86
SFC (lb <sub>m</sub> /hr/lb <sub>f</sub> )	0.585	1.109

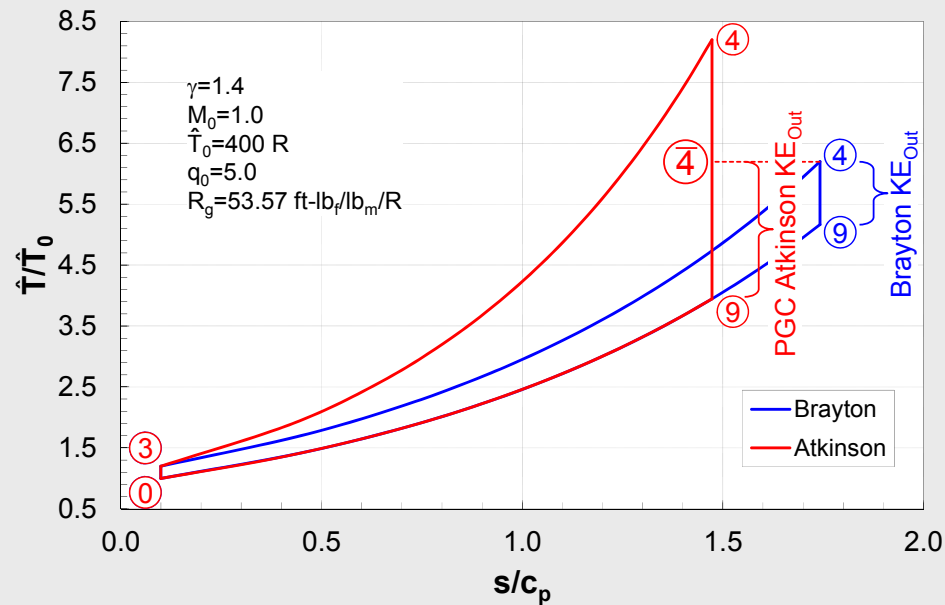
Many Other Studies Available

- AIAA-2013-3623
- AIAA-2004-3396
- Etc.





## Example Benefits



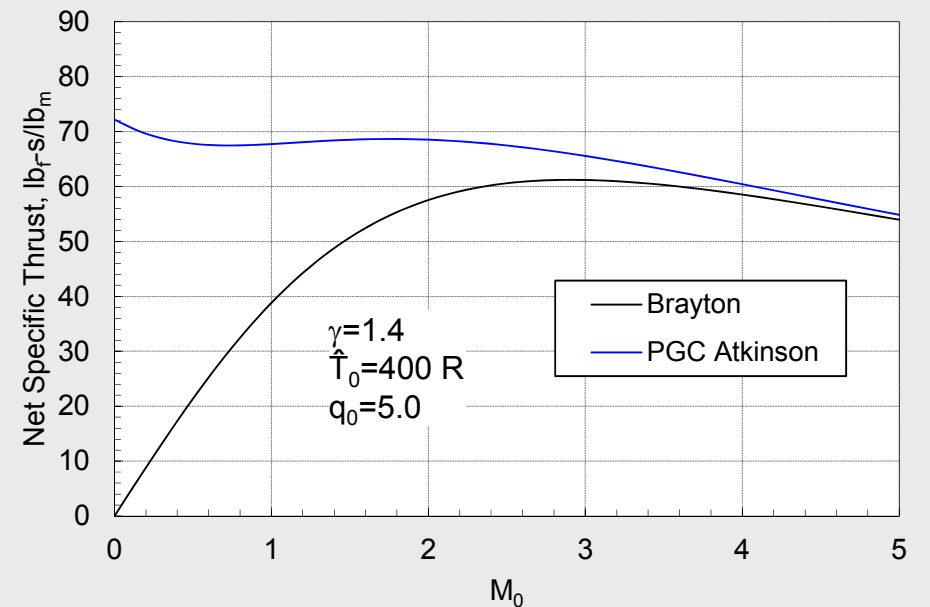
- For the Same Heat Addition:
- Same Mass Averaged  $T_{t4}$
  - More Kinetic Energy Produced
  - Higher Efficiency

## PGC for Ram Devices

Ideal inlet

Ideal nozzle

Brayton  $P_{t4}/P_{t3}=1.0$

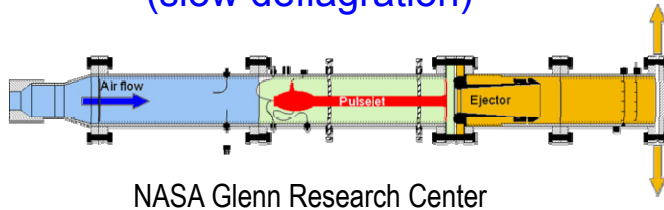




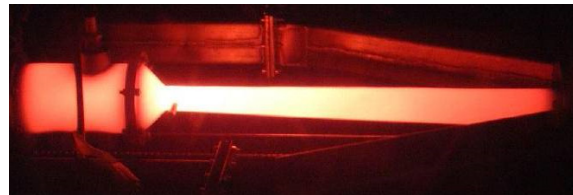
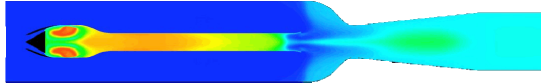


# Implementation Strategies

## Resonant Pulse Combustor (slow deflagration)



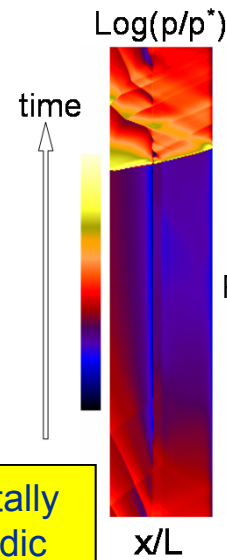
NASA Glenn Research Center



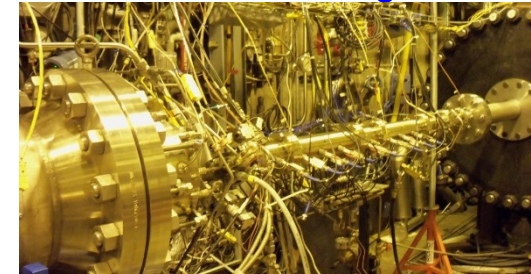
University of Cambridge

All Are Fundamentally  
Unsteady & Periodic

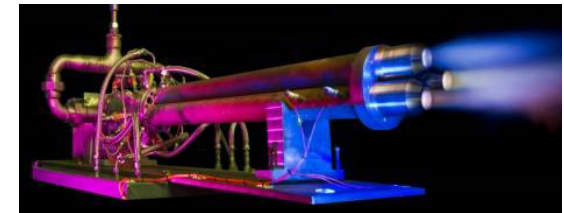
Fill → Burn → Blowdown → Repeat



## Pulsed Detonation Engines



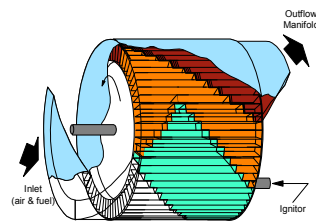
Pratt & Whitney/United Technologies Research Center



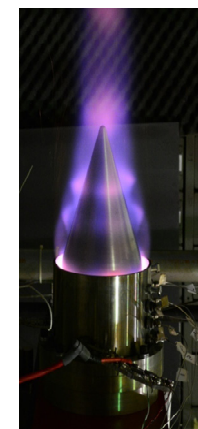
G.E. Global Research Center

## Rotating Detonation Engines

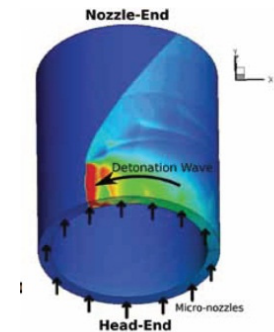
## Internal Combustion Wave Rotor (‘Fast’ Deflagration)



IUPUI/Purdue/LibertyWorks



Air Force Research Laboratory

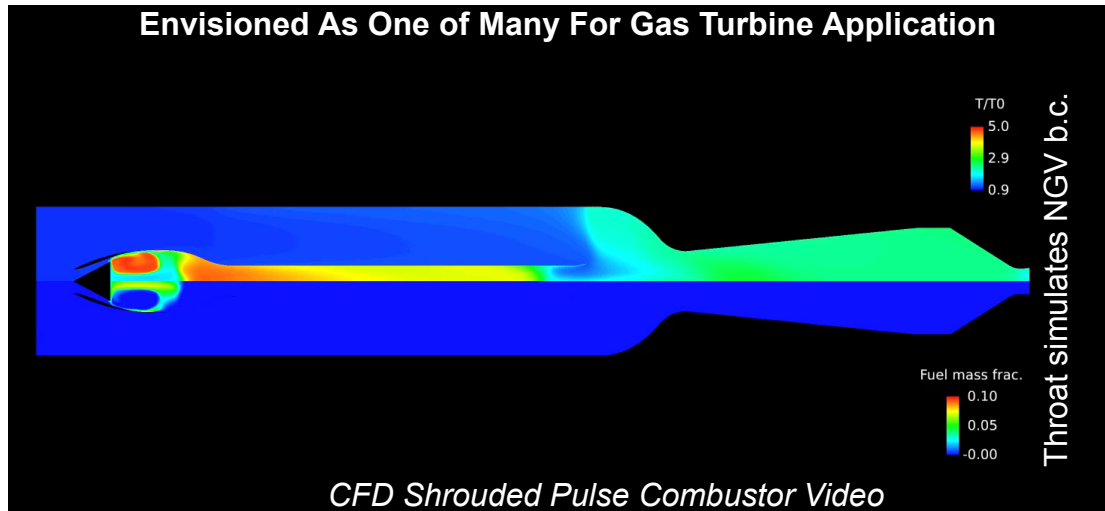


Naval Research  
Laboratory



# Implementation Strategies

## *Resonant Pulse Combustion*



### Characteristics

- Self-sustaining (no spark required)
- Self-aspirating (i.e. operates statically) thus unequivocally demonstrates pressure gain
- Readily operates on liquid fuels
- Few or no moving parts
- Relatively low mechanical/thermal stress
- Relatively benign effluent
- Limited performance potential (confined, not constant volume combustion)



# Implementation Strategies

## Internal Combustion Wave Rotor (ICWR) (‘Fast’ Deflagration)

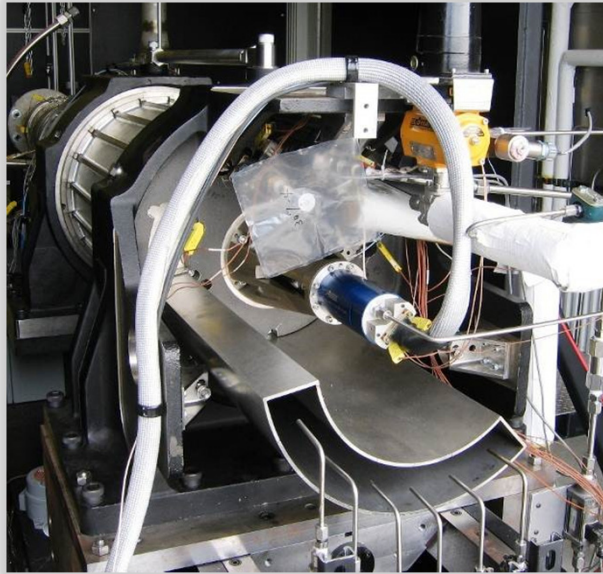
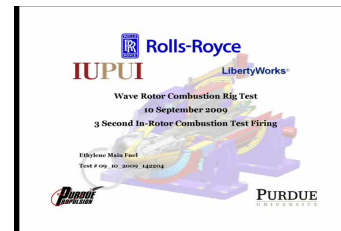
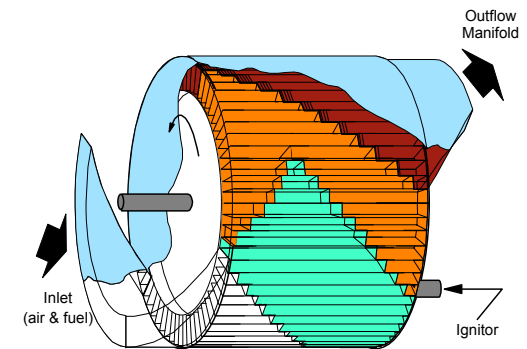


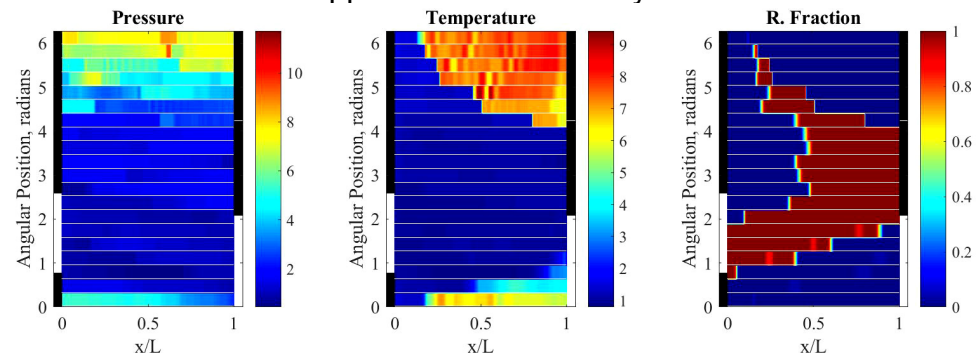
Photo and video courtesy IUPUI and LibertyWorks



Operational Rig Video



Contours of passage fluid properties in  
‘unwrapped’ rotor illustrate cycle



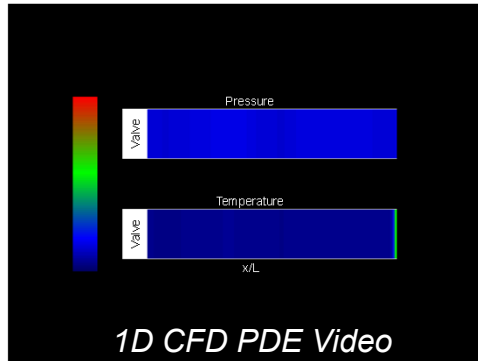
1D CFD Wave Rotor Video

### Characteristics

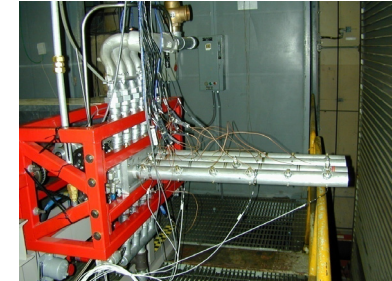
- Flow in ports is nominally steady, though spatially non-uniform
- Rotor is self-cooling is possible
- Very high frequency ignition source req
- Rotation provides valving not power extraction
- Valves implemented at both ends (closest to true constant volume combustion)
- Requires sealing between rotor and endwall
- High performance potential
- Measured pressure gain



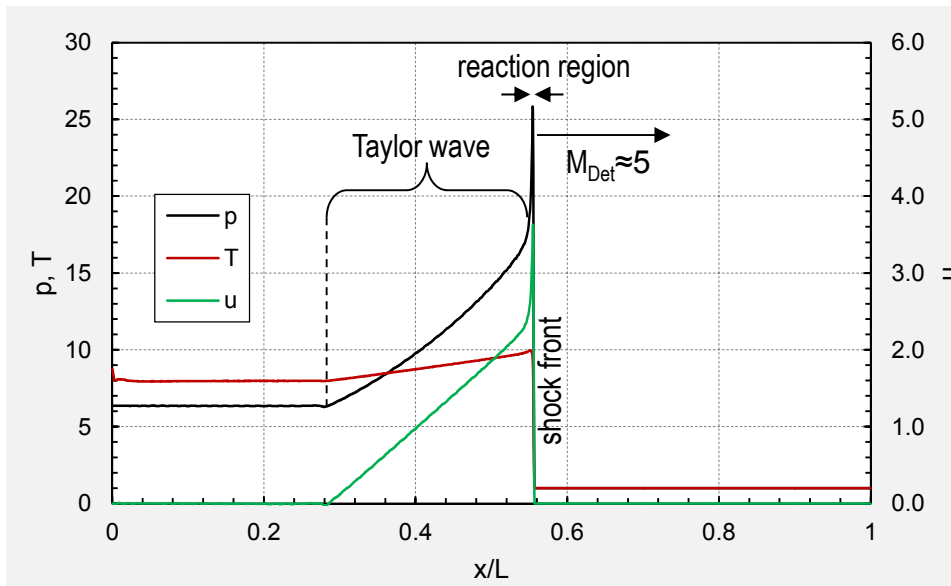
# Implementation Strategies *Pulsed Detonation Engines (PDE)*



Courtesy Naval Postgraduate School



Courtesy Air Force Research Laboratory



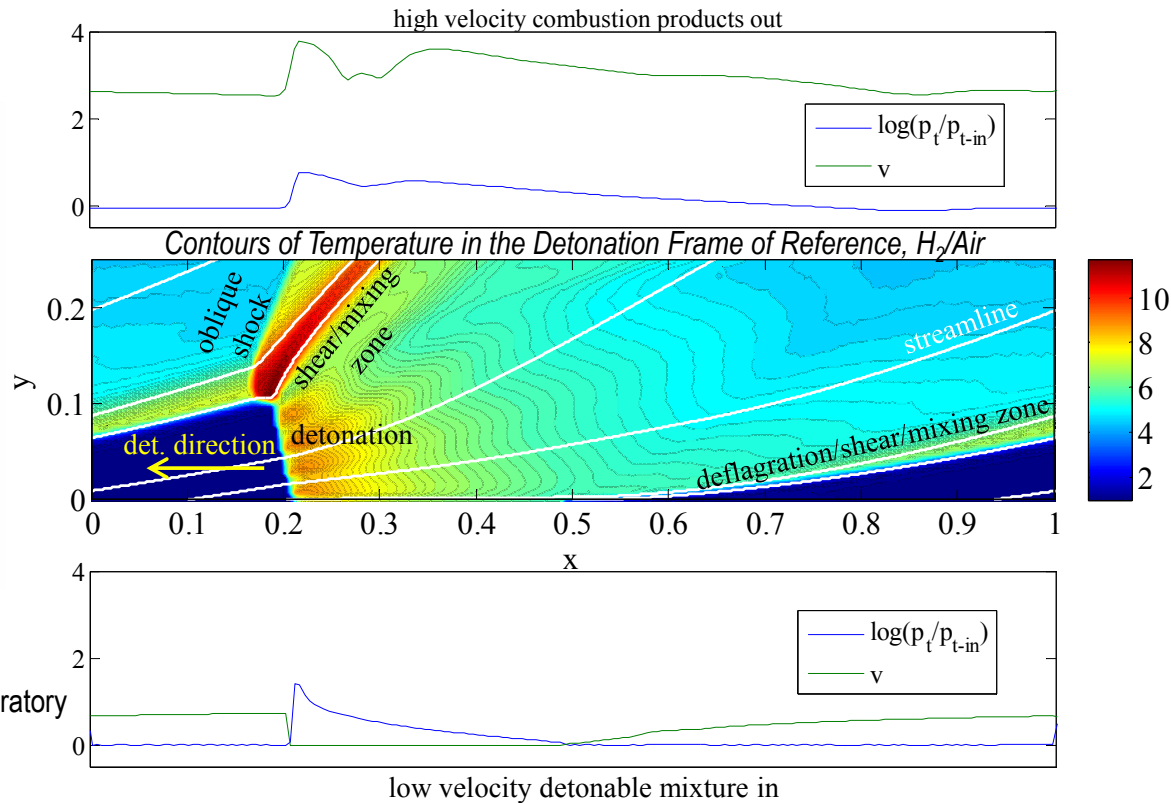
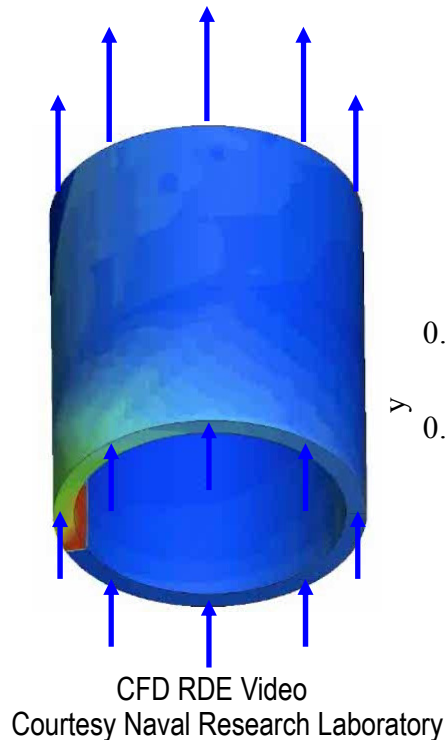
## Characteristics

- Supersonic detonation approximates CV
- Ignition source required
- Deflagration-to-detonation transition obstacles required
- High frequency valves required
- Highly non-uniform effluent
- High performance potential
- Pressure gain measured

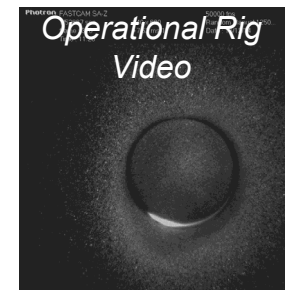




## Recent Implementation Approaches *Rotating Detonation Engines (RDE)*



Courtesy AFRL



Courtesy National Energy  
Technology Laboratory

### Characteristics

- Supersonic detonation (approximating CV) travels circumferentially
- Fluid travels (predominantly) axially
- No ignition source, or DDT obstacles required
- High performance potential
- Very high frequency operation (kHz) – typically mandating aero valve
- Highly non-uniform effluent (but less so than PDE)



## Conclusion

- Pressure Gain Combustion offers the possibility of substantial performance enhancement in propulsion and power applications
- The concept can be thought of as transforming the basic propulsion cycle from Brayton to Atkinson/Humphrey
- Targets improvement at the major source of entropy generation
- There are numerous ways to implement PGC: All are fundamentally unsteady



END